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Article (Accepted Version)

Cartei, Valentina, Banerjee, Robin, Garnham, Alan, Oakhill, Jane, Roberts, Lucy, Anns, Sophie, Bond, Rod and Reby, David (2020) Physiological and perceptual correlates of masculinity in children's voices. Hormones and Behavior, 117. ISSN 0018-506X

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Abstract

Low frequency components (i.e. a low pitch (F0) and low formant spacing (ΔF)) signal high salivary testosterone and height in adult male voices and are associated with high masculinity attributions by unfamiliar listeners (in both men and women). However, the relation between the physiological, acoustic and perceptual dimensions of speakers' masculinity prior to puberty remains unknown. In this study, 110 pre-pubertal children (58 girls), aged 3 to 10, were recorded as they described a cartoon picture. 315 adults (182 women) rated children's perceived masculinity from the voice only after listening to the speakers' audio recordings. On the basis of their voices alone, boys who had higher salivary testosterone levels were rated as more masculine and the relation between testosterone and perceived masculinity was partially mediated by F0. The voices of taller boys were also rated as more masculine, but the relation between height and perceived masculinity was not mediated by the considered acoustic parameters, indicating that acoustic cues other than F0 and ΔF may signal stature. Both boys and girls who had lower F0, were also rated as more masculine, while ΔF did not affect ratings. These findings highlight the interdependence of physiological, acoustic and perceptual dimensions, and suggest that inter-individual variation in male voices, particularly F0, may advertise hormonal masculinity from a very early age.
Keywords: Masculinity; Height; Testosterone; Voice; Formants; Resonance; Fundamental Frequency; Pitch; Children; Gender development

Introduction

Relations between inter-individual differences in androgens (e.g. testosterone levels) and secondary sex characteristics have been demonstrated in several morphological traits, including male facial features (e.g. broader forehead, chin jaw and nose (Marečková et al., 2011) and body build (e.g. larger upper body musculature and broader shoulders (Ross and Ward, 1982)). More recently researchers have investigated whether similar relations exist in the voice, given that acoustic sex differences (adult males having a considerably lower-pitched, deeper voice than adult females or prepubertal children), are also largely attributable to sex hormone action during pubertal development (Johnston et al., 2001). More specifically, the male surge in testosterone during puberty, 20-fold higher in males than females (Fechner, 2003), leads to a permanent enlargement of the male larynx, and thus to a lowering of the average speaking fundamental frequency (F0) compared to women's (associated with the percept of pitch (Titze, 1994)). Testosterone is also responsible for the male-specific descent of the larynx, and overall growth spurt in body height (men are on average up to 6 inches taller than women (Barhum, 2018)), both of which permanently elongate men's vocal tract relative to women's, thus lowering their formants and reducing their spacing (ΔF, associated with voice timbre (Titze, 1994)), compared to women's.

As such, F0 and ΔF are expected to cue for inter-individual differences in hormonal (e.g. circulating testosterone levels) and anatomical (e.g. stature) masculinity. Indeed, negative correlations between testosterone and voice F0 have been found in men through adolescence (Hollien et al., 1994; Hodges-Simeon et al., 2015; Markova et al., 2016; though see Harries et al, 1997) and into adulthood (Dabbs and Mallinger, 1999; Evans et al., 2008; Puts et al., 2012, Aung & Puts 2019), and at least one study reports negative, though weaker, correlations between testosterone and men's ΔF (Bruckert et al., 2006). In a mirroring pattern, women's voices appear to communicate biological femininity, with F0 increasing just before or at peak fertility in their menstrual cycle (Fischer et al., 2011, Bryant and Haselton, 2009, but see Puts et al., 2013). Adult body height is also predicted by ΔF (up to 10% of variance), and to a far lesser extent, F0 (0.5% of variance in women and 2% in men on average) (see Pisanski et al., 2014 for a review). On a perceptual level, listeners associate greater masculinity in men and women with lower F0 and ΔF in natural and artificial voices (Feinberg et al., 2005; Feinberg et al., 2008; Pisanski et al., 2012). More recently, Cartei and colleagues (2014a) used path analyses to confirm these relations between biological, acoustic and perceptual correlates of masculinity in adult males, showing that men who are taller and have higher testosterone levels tend to speak with lower fundamental frequency and lower formant frequency spacing, and that their voices tend to be rated as more masculine by female listeners.

While pubertal androgens considerably increase the sex dimorphism in secondary sex characteristics, including differences in F0 and ΔF, they may also affect individual differences in voice masculinity in childhood, as already found for other secondary sex characteristics, such as facial shape and features (Meindi et al, 2012; Whitehouse et al., 2015). Indeed, a recent acoustic study has identified a positive association between a possible index of prenatal testosterone exposure (the ratio of the lengths of the second to fourth digits of the right hand (2D:4D) at 5 years of age and the F0 at both four months and 5 years of age in both sexes, suggesting that inter-individual differences in post-pubertal speech may arise well before puberty (Levrero et al., 2018).

Here we report the first investigation of a link between inter-individual pre-pubertal differences in biological indexes of masculinity (circulating testosterone levels, body height) and variation in F0 and ΔF, as well as their influence on masculinity attributions made by adult listeners. As already found in adult speakers (Cartei et al., 2014a), we predicted that child speakers who are taller and have higher salivary testosterone levels, will also have lower voice fundamental frequency (F0) and formant spacing (ΔF), and will be rated as more masculine by listeners. We also predicted that the relation between testosterone and perceived masculinity would be more strongly mediated by F0, while the relation between height and perceived masculinity would be more strongly mediated by ΔF.

Material and Methods

Participants

Speakers were 110 children between 3 and 10 years of age (58 girls: mean age = 7.28, SD=2.25, 52 boys: mean age = 7.42, SD=1.94). None were currently suffering from any conditions that might affect their voice (e.g. colds, sore throats). Parents provided informed written consent, and children provided verbal assent on the day. Listeners were 315 undergraduate and postgraduate students (mean age 20.7, SD =2.9 years, 182 women) with no hearing impairments who were recruited into the study from psychology, biology and neuroscience courses at the local university.

Audio Recordings and sound analyses. 70 children were audio-recorded on campus, and 40 children were tested at their nurseries, and in four primary schools as part of a larger voice production study. All recordings were performed using a Zoom H1 handheld recorder positioned at approximately 30 cm from the participant, at a constant sound recording level (mean intensity 60.34 dB ± 1.95 dB). Sound files were recorded at 44.1 kHz, 16 bits and saved in WAV format. Acoustic analysis on children's audio-recordings were performed in PRAAT v.6.0.28 on Mac (Boersma and Weenink, 2019). In order to elicit spontaneous speech from children, while minimising content-dependent phonetic and fluency biases, we asked all children to describe the same A4-sized, colour printed scene of the popular cartoon Peppa Pig (see Appendix), as previously used by Levrero and colleagues (2018). From the original recordings, we then selected the section where all children described Peppa's toys lying on the floor in the cartoon picture, cutting the selection to where the description ended with a falling tone, and discarding inflexions for questions. Recordings were also edited manually to remove all silences, nonverbal vocalisations (e.g., laughter, loud breathing or nonverbal interjections) acute background noises and the experimenter's questions. To focus on the effect of frequency components and remove the potential effect of intensity on masculinity ratings (e.g. higher-intensity adult voices tend to be perceived as more masculine - Hardy et al., 2018), samples were then scaled in intensity to an average 60dB level using the "Scale intensity" command in PRAAT.

The voice stimuli resulted in concatenated speech sequences ranging between 6s and 13s seconds (mean duration 8.5 ± 4.3 s). To extract the mean F0, the PRAAT time step was set to 0.01 with a search range of 100-500 Hz. Measurement of formants F1-F4 was undertaken via Praat's Burg linear predictive coding algorithm with the initial settings of maximum formant 8000 Hz and formant number 5, dynamic range 30 dB, length of the analysis window 0.2 s. Formant values were then overlaid on a spectrogram and maximum formant (range: 6500Hz-8200Hz) and formant number parameters (from 4 to 6) were manually adjusted until the best visual fit of predicted onto observed formants was obtained. Formant F_1 to F_4 values of each recording were then used to derive the average formant spacing (ΔF), which corresponds to the average distance between any two adjacent formants ($\Delta F = F_{i+1} - F_i$), as in Cartei and colleagues (2019).

Physiological indexes of masculinity. After the audio recordings, children's height and saliva samples for testosterone analysis were taken. Height was measured to the nearest 0.1cm using a Seca Leicester stadiometer, from the top of the participant's head to the soles of his or her feet (shoes off and feet together), with the participant standing erect and looking straight ahead. Mean body height (± SD) was 126.8 ± 13.66 for boys, and 122.9± 14.61 for girls. Saliva samples were obtained after body height measurements from children using Salimetrics Children's Swab sampling device (Salimetrics, 2014), which allowed one end to be held by an adult (parent or researcher), while the other end was placed in the child's mouth. All samples were collected in the afternoon (M =3.15 pm, range = 1pm-4.30pm) to minimise the effect of diurnal variation in F0 and testosterone levels (Evans et al., 2008). To minimize the risk of saliva contamination, children were instructed not to consume food for at least 30 min prior before testing and were given a small glass of water to rinse their mouth after the audio recordings prior to saliva collection. The samples were immediately frozen and stored at -20C until analysis. Saliva samples were assayed for testosterone at the Biomarker Analysis Laboratory of Anglia Ruskin University (Salimetrics-approved Centre of Excellence) using the commonly used competitive Enzyme Immunoassay Kit by Salimetrics (2014). Samples were assayed in duplicate, and those yielding coefficients of variation (CVs) between duplicate wells in the highest 10% of the range were re-assayed once to maximize measurement accuracy. The average intra-assay and inter-assay CVs were 5.13%, and 7.51% (values below 10% and 15%, respectively, are generally acceptable – Salimetrics, 2019). Testosterone concentrations in saliva reflect those in the free (non-protein bound) fraction of plasma (Riad-Fahmy et al., 1982; Vittek et al., 1985; Navarro et al., 1986).

Playback experiment. To minimise listeners' fatigue and to avoid speaker age as a confounder on masculinity ratings (e.g. older children having lower F0 and ΔF and thus sounding more masculine than younger children), listeners were split into eight groups and each group was asked to give perceived masculinity/femininity ratings to one of four subsets comprising between 30 and 40 voice stimuli from boy and girl speakers, grouped by speaker age: 3-5 year olds (recruited from nursery), 6-7 year olds (recruited from UK School Years 1-2), 8-9 year olds (recruited from Years 3-4) and 9-10 year olds (from Years 5-6). Therefore, two different groups of listeners rated the same subset of speakers. Listeners from the same group were tested together in the same room, but completed the experiment individually via a custom computer interface that was designed in PRAAT. They wore a set of USB headphones and were required to first listen to a test sound (a child's voice not included in the actual experiment) at a pre-set volume. They were allowed to adjust the volume to a comfortable level, and 32 participants changed their volume settings. A Multiple Forced Choice (MFC) PRAAT script was used for the actual playback experiment. Adults listened to all the speakers of the same sex uttering the cartoon description (one group of listeners rated first girls, then boys, and the other group of listeners rated first boys, then girls), and the order of the voice stimuli within the set was randomized. Rest-breaks were scheduled after every 15 voice stimuli. At the start of the experiment, participants were first told the sex and age of the speakers that they were asked to rate (e.g. "You will listen to voices by boys/girls in Years 1 and 2"). Then, for each stimulus they were asked to decide how masculine/ feminine the speaker was (e.g. "Please rate how masculine/feminine this boy/girl is") by clicking the respective button on the screen (for girls the scale read: 1= "very masculine" to 7= "very feminine" and the reverse scale was used for boys).

Results

Age and Sex effects on physiological indexes of masculinity

We ran two Linear Mixed models (LMM) testing the main and interaction effects of sex (fixed factor) and age (covariate) on testosterone and height (continuous outcome variables). Partial eta-squared η^2 was used to estimate effect sizes. Participant identity was included as subject variable. The main effect of sex was significant on salivary testosterone levels, $F(1,106)=15.35$, $p<.001$, $\eta^2=.07$ with boys having higher concentrations (± SD) 0.03 ± 0.02 nmol/L than girls, 0.02 ± 0.01 nmol/L. There was a significant interaction between sex and age, $F(1,106)=15.35$, $p<.001$, $\eta^2=.04$ with boys' concentrations remaining stable across the age range, while girls' concentrations increased with age. There was a significant main effect of age on height, with both sexes growing taller with age, $F(1,102)=592.35$, $<.01$, $\eta^2=.86$. Neither the effect of sex nor its interaction with age was significant, $p>.05$.

Age and Sex effects on F0 and ΔF of children's natural voices

We ran two LMMs with sex as fixed factor and age as covariate on F0 and ΔF (as continuous outcome variables), to test for sex and age-related differences in our sample. Mean F0 (± SD) across the sample was 240.5 ± 38.2 Hz for girls and 234.2 ± 30 Hz for boys. Mean ΔF (± SD) across the sample was 1452.8 ± 77.7 Hz for girls and 1409.1 ± 89.1 Hz for boys. Sex had a significant main effect on ΔF, $F(1,106)=12.61$, $p=.001$, $\eta^2=.33$, but not on F0, $p>.05$. Age had a significant effect on both F0, $F(1,106)=50.61$, $p<.001$, $\eta^2=.35$ (Figure 1a, 1b), and ΔF, $F(1,106)=114.73$, $p<.001$, $\eta^2=.53$ (Figure 1c, 1d).

Reliability of listeners' ratings

Preliminary analyses showed no significant differences in ratings between male and female listeners, therefore perceptual ratings were combined in subsequent analyses. Mean ratings across listeners (± SD) were 4.4 ±0.8 for girls (on a scale 1=very masculine to 5=very feminine), and 4.2±0.9 for boys (on a scale 1=very feminine to

5=very masculine). Inter- and Intra-rater reliability were obtained using, respectively, Cronbach's alpha (α), and Intra-class Correlation (ICC – average measures, 2-way random) on masculinity ratings made by listeners in each group (nursery, yr 1-2, yr 3-4, yr 5-6), separately for boy and girl speakers. Inter-rater reliability was high, with α=.98-.99 for boys, and α =.95-.97 for girls (Gliem & Gliem, 2003). Intra-rater reliability was also in the excellent range, with ICC ranging from 0.95 to 0.99 (Cicchetti, 1994). Given the listeners' general agreement on masculinity ratings, mean ratings across listeners for each speaker were used in the main path analysis.

Main analysis (Path analysis)

In order to test multiple pathways from biological (testosterone, height) and acoustic (F0, ΔF) characteristics of girl and boy speakers to masculinity ratings of their voices, we ran two-level (speaker nested within listeners) path analyses, one for the boys' and one for the girls' data, with testosterone and height as the exogenous variables, F0 and ΔF as the mediating variables, and mean masculinity (for boys) and femininity (for girls) ratings as the endogenous variable. The acoustic and physiological variables were corrected for age (standardized residuals) before being entered in the fully saturated models in order to reduce the number of parameters in the models, thus maximizing power, while controlling for the observed effects of age on the physiological and acoustic variables. The diagrams for the boys' and girls' model with the standardised path coefficients are shown in Figures 2 and 3, respectively. The speakers' sample size was over the recommended 10 cases per parameter necessary to perform this analysis (Kline, 2011). We fitted the model using *lavaan* version 0.6-3 (Rosseel, 2019) in R v. 3.5.1 (all R code for the analysis is available in the Supplemental Materials). We used maximum likelihood estimation with bootstrapping of 10000 samples in line with best practice (Mallinckrodt et al., 2006). Latent factors were standardised, allowing free estimation of all factor loadings. The strength of the associations (path coefficients) between the variables was interpreted following Campbell and Swinscow (1996): values of ρ .00-.19 are regarded as very weak, .20-.39 as weak, .40-.59 as moderate, .60-.79 as strong, and .80-1.00 as very strong. The goodness of fit of the path models was evaluated using the chi-square value and alternative fit indices, such as TLI, CFI and RMSEA. Non-significant chi-square, values of TLI and CFI values that are greater than 0.95 (Byrne, 2001) and RMSEA values of less than .05 indicate very close model-to-data fit (Browne and Cudeck, 1993). The hypothesised models fit the data well (boys: $\chi^2(10)=5.7$, $p>.05$; TLI=1, CFI=1, RMSEA=0; girls: $\chi^2(10)=13.4$, $p>.05$; TLI=1, CFI=1, RMSEA=0).

Biological and acoustic characteristics. In boys, higher salivary testosterone concentrations significantly and negatively correlated with the acoustic variables: boys with higher testosterone levels also spoke with lower F0 and ΔF. The correlation between testosterone and F0 was moderate ($\rho=-.48$, $p<.001$, scatterplots in Figure S1a,b), while the correlation between testosterone and ΔF was weak ($\rho=-.26$, $p=.034$, scatterplots in Figure S1c,d). No other significant correlations between biological and acoustic characteristics were found.

Acoustic characteristics and listeners' judgements. Girls with higher F0 received significantly higher femininity ratings ($\rho=.33$, $p=.023$), and boys with lower F0 received significantly higher masculinity ratings ($\rho=-.40$, $p<.002$, scatterplots in Figure S2a,b). No significant relations were found between boys' and girls' ΔF and ratings, ps>.05 (scatterplots in Figure S2c,d). F0 and ΔF were not significantly correlated in either sex ($\rho=.11$, ps> .05).

Biological characteristics and listeners' judgements. In boys, the total effect of testosterone on perceived masculinity was weak, but significant ($\rho=.24$, $p=.046$; scatterplots in Figure S3). There was also a weak, but significant indirect path via F0 between testosterone and perceived masculinity ($\rho=.19$, $p=.02$, CI: .06-.35), while the direct path between the two variables was not significant, $p>.05$. There was a moderate, but significant effect of height on perceived masculinity ($\rho=.52$, $p<.001$). The direct path between height and masculinity ratings was significant, and strength of the association was moderate ($\rho=.44$, $p<.001$), while there were no significant indirect paths between the two variables, revealing that the relation between height and perceived masculinity was not mediated by the measured acoustic variables (F0 and ΔF). None of the paths between the biological variables and perceived femininity was significant in girls, ps >.05.

Discussion

The present study reveals significant relations between physiological, acoustic and perceptual characteristics of masculinity, which are discussed in the paragraphs below.

Biological characteristics and voice cues

In line with our hypothesis, we found that the boys who have higher salivary testosterone levels tend to speak with lower fundamental frequency and, to a weaker extent, lower ΔF, while no significant relations between testosterone and the two acoustic variables were found in girls. While previous work identified a negative link between testosterone and F0 in pubertal males and adult men (Pedersen et al., 1986; Evans et al., 2008; Cartei et al., 2014a), our results suggest that testosterone may affect sex-related voice cues well before puberty, at least in males. Further corroborating this hypothesis, a recent longitudinal acoustic study (Fouquet et al., 2016) found that individual differences in men's *F*0 emerge by age 7 and are stable throughout adulthood. We also found that, while boys had higher salivary testosterone levels than girls, these levels slightly increased with age in girls only. These results are in line with previous studies (Sizonenko and Paunier, 1975; Ostatnikova et al., 2002), and may reflect the close relationship between increases in testicular volume and salivary testosterone concentrations occurring in boys from about age 12 (Albertsson-Wikland et al, 1997). Given the observed sex-specific differences in testosterone levels, we propose that the differential pre-pubertal effects of testosterone on F0 between the two sexes may be caused by sex differences in sensitivity of the hormone receptors in the vocal fold mucosa (Newman et al., 2000). In support of this hypothesis, a recent study found that female laryngeal tissue is less sensitive to androgen exposure between birth and adrenarche than during other periods (Grisa et al., 2012). Yet by adulthood, women's larynx is sensitive to testosterone, as shown by the irreversible reduction in F0 following testosterone injections in women (Hollien and Shipp, 1972) and the decrease in female F0 linked to an increased testosterone-to-estrogen ratio after menopause (Stoicheff, 2014). It is also possible that female F0 may be differentially affected by sex hormones other than testosterone. For example, laryngeal tissues are also characterised by receptors to oestradiol and progesterone (Prelevic, 2000; Voelter et al., 2008), which are typically higher in females than in males (Derntl et al., 2014). Given that female puberty (Pedersen et al., 1990), pregnancy (Hamdan et al., 2009), menopause (Abitbol et al., 1999; Caruso et al., 2000), hormone replacement therapy (Firat et al., 2009) and hormonal contraceptive use (Amir et al., 2002) have all been found to affect both these hormones and women's vocal acoustics, future work could investigate whether these hormones are predictors of F0 and ΔF in child and adult speakers.

Turning to the relation between height and sex-related voice cues, it has been previously suggested that taller individuals will produce lower ΔF than smaller individuals, because longer vocal tracts are predicted to produce lower and more closely spaced formants, in line with the source-filter theory of speech (Fant, 1960). However, because thicker and longer vocal folds vibrate at lower frequencies, taller individuals may have larger larynges which in turn would also produce lower F0 than those of smaller individuals (Fitch and Hauser, 2003; Morton, 1977; Titze, 1994). While we found that older children had lower F0 and ΔF than younger children, tracking concomitant age-related increases in height (Hirano et al., 1983), once age differences were taken into account our results did not support the hypothesis of a significant association between height and either F0 or ΔF. The absence of a link between height and F0 may be due to the fact that the human larynx lies outside the bony confines of the skull, and thus is relatively unconstrained by body size (González et al., 2004). On the other hand, the anatomical vocal tract (VTL), which is inversely related to ΔF, is comparatively dependent upon skeletal size, and differences in ΔF between-sex and age-class differences largely reflect such dependency (Kent and Vorperian, 2018). Yet, previous research on within sex-age relations in adults has failed to identify strong correlations between height and ΔF: in a recent meta-analysis, individual formant-based VTL estimates were found to only explain up to 10% of the height variance within sexes (Pisanski et al., 2014). We propose that voice modulation may at least partially account for the observed lack of a significant association between inter-individual variation in height and ΔF in children, and the weak relations previously reported in adults. Because articulatory behaviours of larynx and lips dynamically alter the size and shape of the vocal tract (e.g. moving the larynx up/down, and spreading/rounding one's lips will shorten/lengthen the vocal tract), speakers may accentuate or downplay the relatively small within-sex differences in vocal tract length, and thus ΔF. Indeed, children and adults have been found to spontaneously shift ΔF to sound more or less masculine (Cartei, Cowles, and Reby, 2012; Cartei, et al., 2014b), suggesting that speakers may routinely engage (though perhaps unconsciously) in these vocal behaviours.

Voice cues and listeners' ratings

We also found that lower-pitched voices in both boys and girls were rated as more masculine than higher-pitched voices, but there were no significant associations between ΔF variation in children's voices and their perceived masculinity. Most psychoacoustic studies with adults report that F0 plays a greater role compared to ΔF in cueing for the masculinity of adult speakers (Gelfer and Mikos, 2005; Hillebrand and Clark, 2009; but see Pisanski et al., 2011), reflecting the greater dimorphism of F0 over ΔF in adult voices (F0 ratio: 1.81 versus ΔF ratio: 1.20 - Titze, 1994). Given that pre-pubertal voices are sexually dimorphic in ΔF only (Titze, 1994), it would be reasonable to predict that prior to puberty listeners would rely on ΔF more heavily than F0 when making masculinity attributions. Indeed, two recent psychoacoustic studies have shown that relatively small ΔF shifts (between 2% and 12%) strongly affect masculinity attributions of child speakers by both adult (Cartei and Reby, 2013) and child raters (Cartei et al., 2019). However, this prediction was not supported by our results. This may be because the magnitude of the variation in the F0 of our sample (as estimated by the Coefficient of Variation, calculated by dividing SD by the mean), was three times bigger than the magnitude of variation in ΔF. Thus, it is possible the reported association between F0 and masculinity may simply reflect the perceptual disparity between these two parameters, rather than greater salience of F0 over ΔF *per se*.

To what extent do F0 and ΔF mediate the relation between size, androgens and perceived masculinity?

In line with our hypothesis we found that, in boys only, the relation between testosterone and perceived masculinity was mainly mediated by F0, with higher testosterone boys speaking with lower F0 and being perceived as more masculine than their lower-testosterone counterparts. Salivary testosterone levels have been found to positively correlate with stereotypically masculine traits such as physical aggressive behaviour in children as young as four (Sanchez-Martin, 2000), and in adults (Book et al., 2001 for a review). While the examination of the relation between F0 and masculinity traits in childhood remains largely unexplored, adults' F0 correlates with other indexes of masculinity such as physical strength (in Hadza men (Puts et al., 2012)), and dominance rank (Wolff and Puts, 2010). Similarly, voice F0 may correlate with other indexes of masculinity in males, as a consequence of exposure to androgens, from a very early age. We also found that height positively correlated with masculinity ratings of voice in both sexes, with taller children being perceived as more masculine. In adult men, height has been found to positively correlate with typical masculine traits such as physical aggression (Archer and Thanzami, 2007), fighting ability (among the

Tsimane (von Rueden et al., 2008)), greater weight and arm strength (though not with circulating testosterone: Kempe et al., 2013), suggesting that height is a reliable index of male masculinity. The fact that the significant relation between height and masculinity ratings was not mediated by either F0 or ΔF, indicates that acoustic cues other than those measured here encode information about body height. For example, a recent study showed that taller men produce less differentiated vowels and are also less likely to produce the perceptually clearer aspirated variant of /t/ (Kempe et al., 2013). Thus, future path analyses of perceived masculinity could include the size of vowel space as a mediator.

Conclusions

This study investigated for the first time the inter-relations of biological (body height and testosterone), acoustic (F0 and ΔF) and perceptual masculinity (adults' ratings) in pre-pubertal children, thus complementing previous research with adult speakers in this area. As previously observed in men (Cartei et al., 2014a), this study found links between all three dimensions in boys, suggesting the early onset of these associations, at least in males. Further investigations could expand the present findings by considering additional biological correlates to masculinity, including exposure to sex hormones in the prenatal environment (as estimated by the second-to-fourth digit ratio, 2D:4D), given their weak positive association with testosterone levels in men (Hönekopp et al. 2007, Muller et al., 2011; though see: Manning et al., 2004), and with facial masculine features in both child (Meindil et al., 2012) and adult (Schaefer et al, 2005) males, as well as voice pitch of children of both sexes from 3 months to 5 years of age (Levrero et al., 2018). Acoustically, other voice characteristics in adults that are associated with masculine attributes (e.g. toughness), such as reduced vowel space size (less articulatory clarity (Kempe, Puts and Cárdenas, 2013)) and F0 variation (less intonation (Leongomez et al. 2014; Hodges-Simeon et al., 2010; Terango, 1966)), may in turn signal various aspects of biological masculinity and could therefore be included in future investigations. The present paradigm could also be improved by removing the effect of age (here largely mitigated by asking listeners to rate children within a restricted age range) on the observed biological and acoustic variables, as well as its potential effect on ratings (e.g. on average, older children have lower F0 and ΔF and thus would sound more masculine). This could be achieved by replicating the study using large samples for each age category. Ratings on everyday speech from a variety of contexts (e.g. when engaging in masculine/feminine activities, speaking to same-sex/ opposite-sex peers) by both child as well as adult listeners, would also improve the ecological validity of the present paradigm. Finally, future investigations of longitudinal nature in a wider set of cultures, are needed to confirm the universality of the observed associations and their relative stability throughout the lifespan.

Acknowledgements

We are grateful to the children and their parents who agreed to take part in the study, and to the head teachers and staff of the involved primary schools.

Funding: This work was supported by the The Leverhulme Trust [grant number: RPG-2016-396]. Prof Reby was also supported by the University of Lyon IDEXLYON project as part of the "Programme Investissements d'Avenir" (ANR-16-IDEX-0005).

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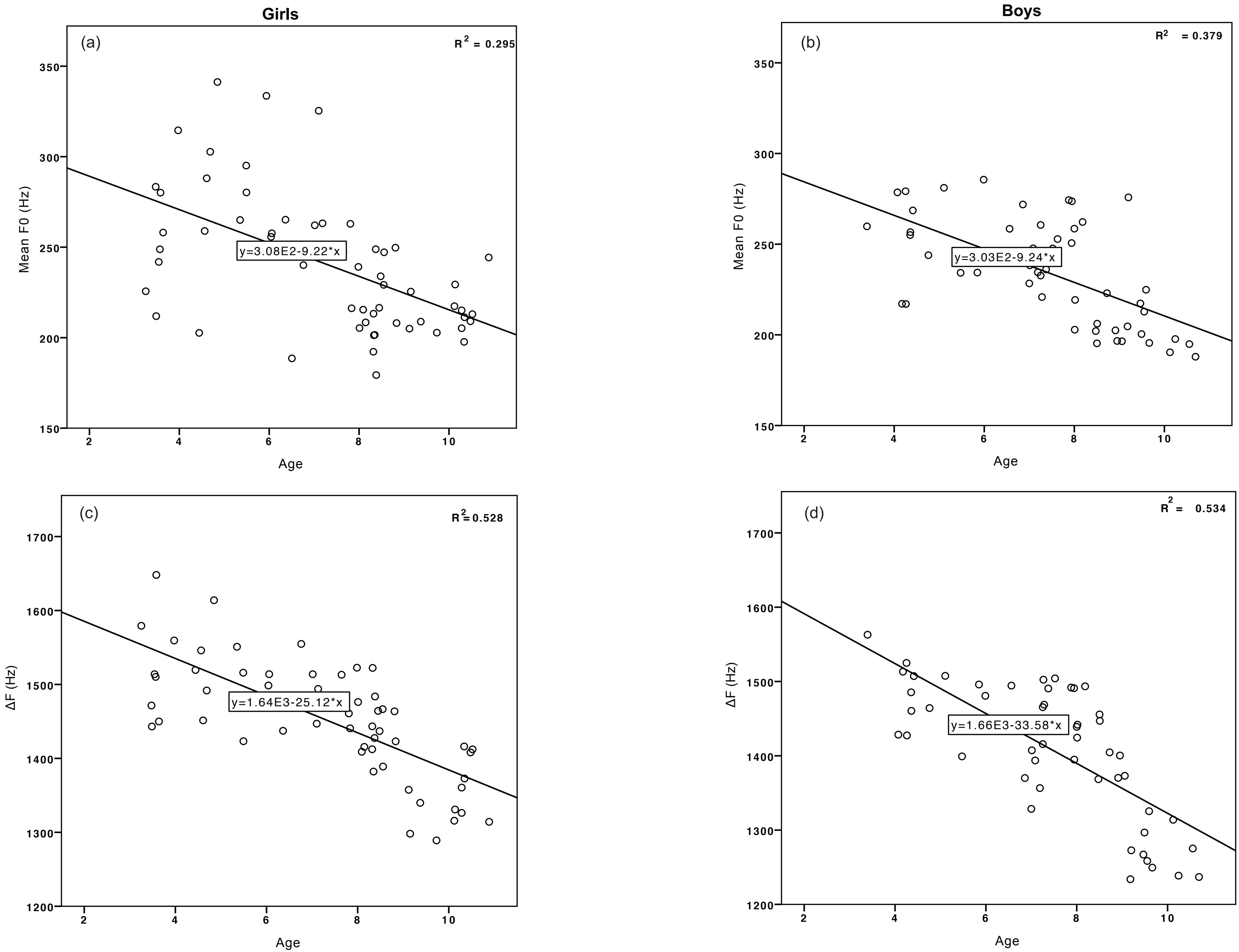
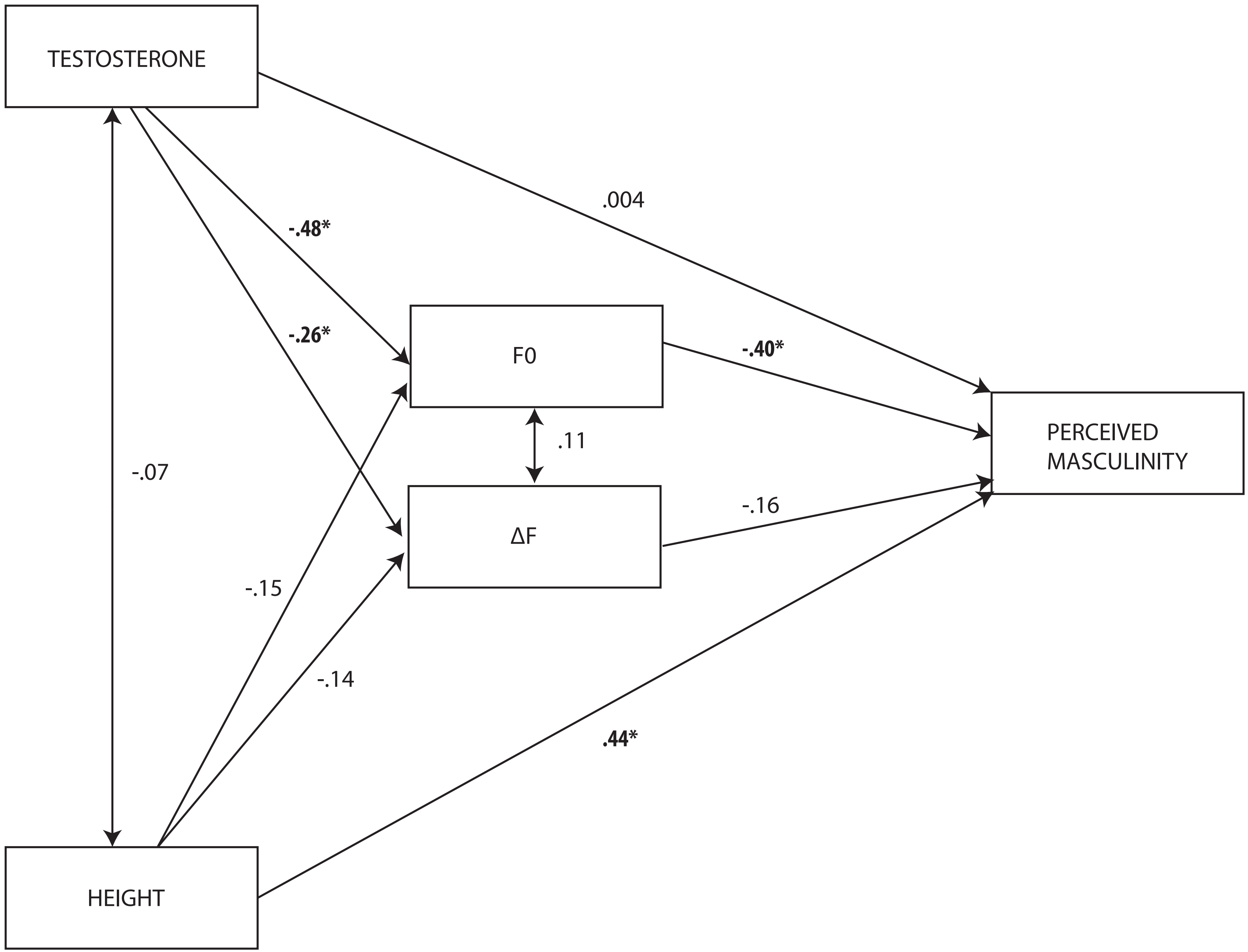
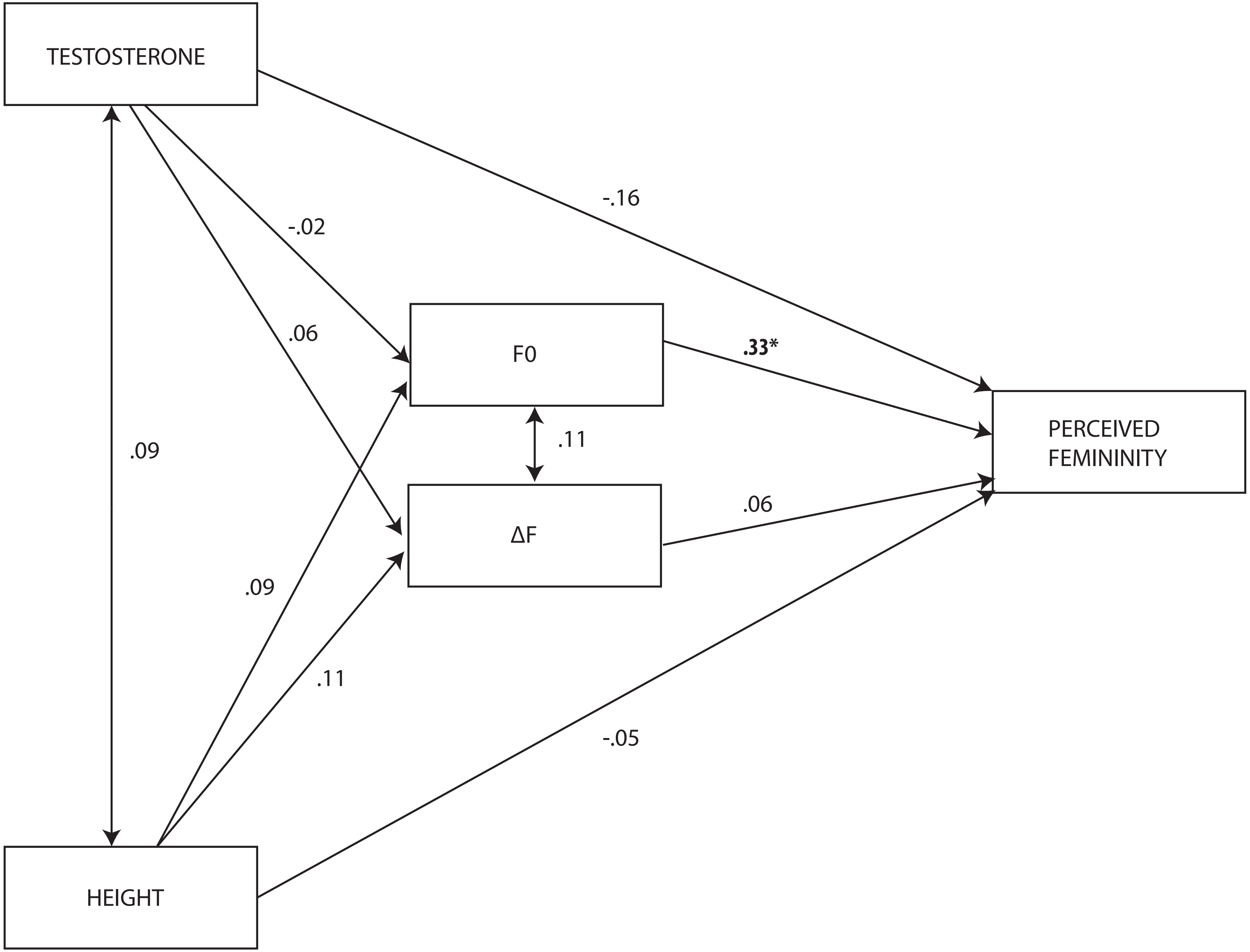
Can you please describe what Peppa is doing?

What else can you see?



Girls
Boys
(a)
R^2 = 0.295
y=3.08E2-9.22*x
Mean F0 (Hz)
Age
(b)
R^2 = 0.379
y=3.03E2-9.24*x
Mean F0 (Hz)
Age
(c)
R^2 = 0.528
y=1.64E3-25.12*x
ΔF (Hz)
Age
(d)
R^2 = 0.534
y=1.66E3-33.58*x
ΔF (Hz)
Age


TESTOSTERONE
.004
-.48*
-.26*
F0
-.40*
.11
PERCEIVED
MASCULINITY
-.07
ΔF
-.16
-.15
-.14
.44*
HEIGHT


TESTOSTERONE
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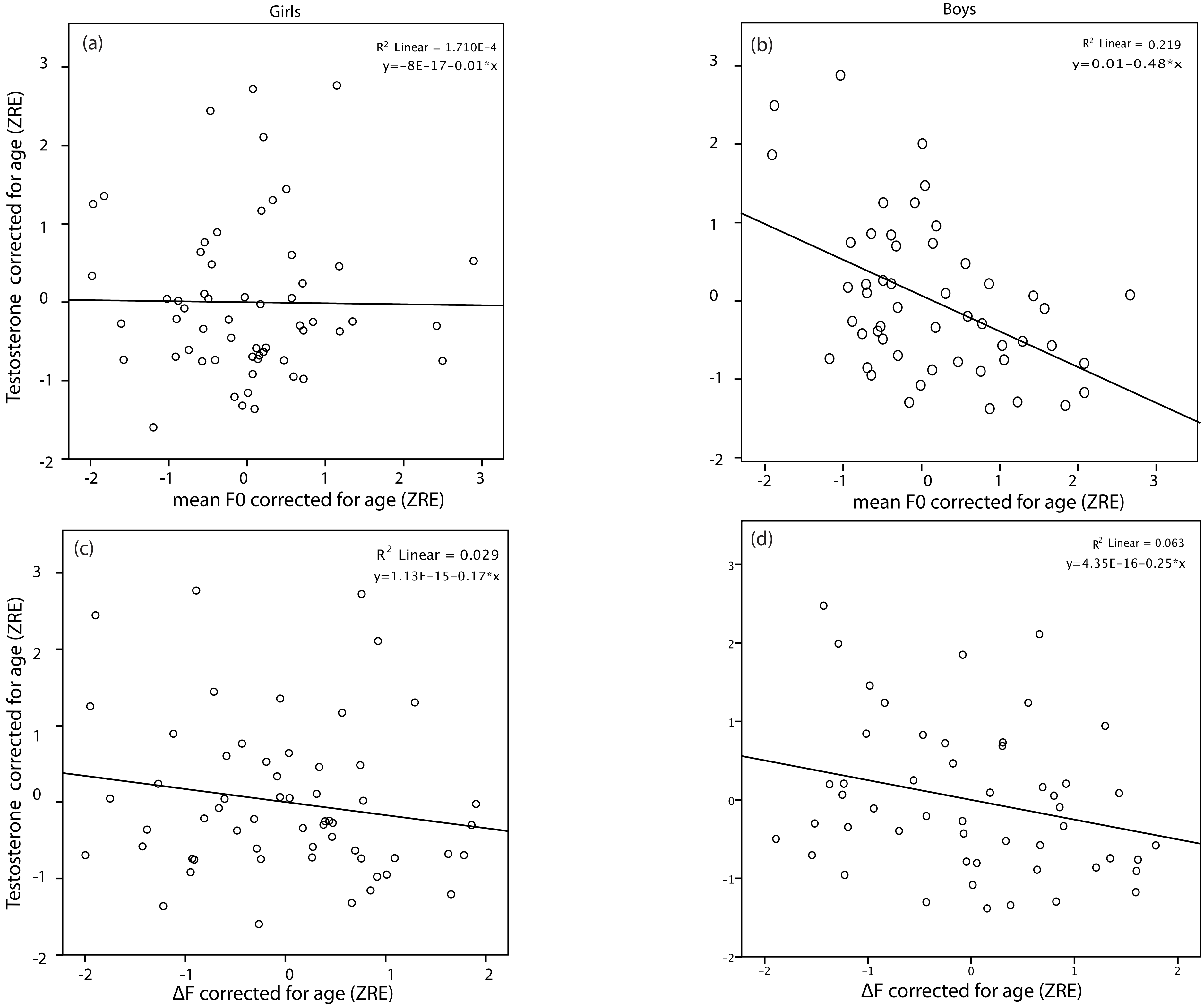
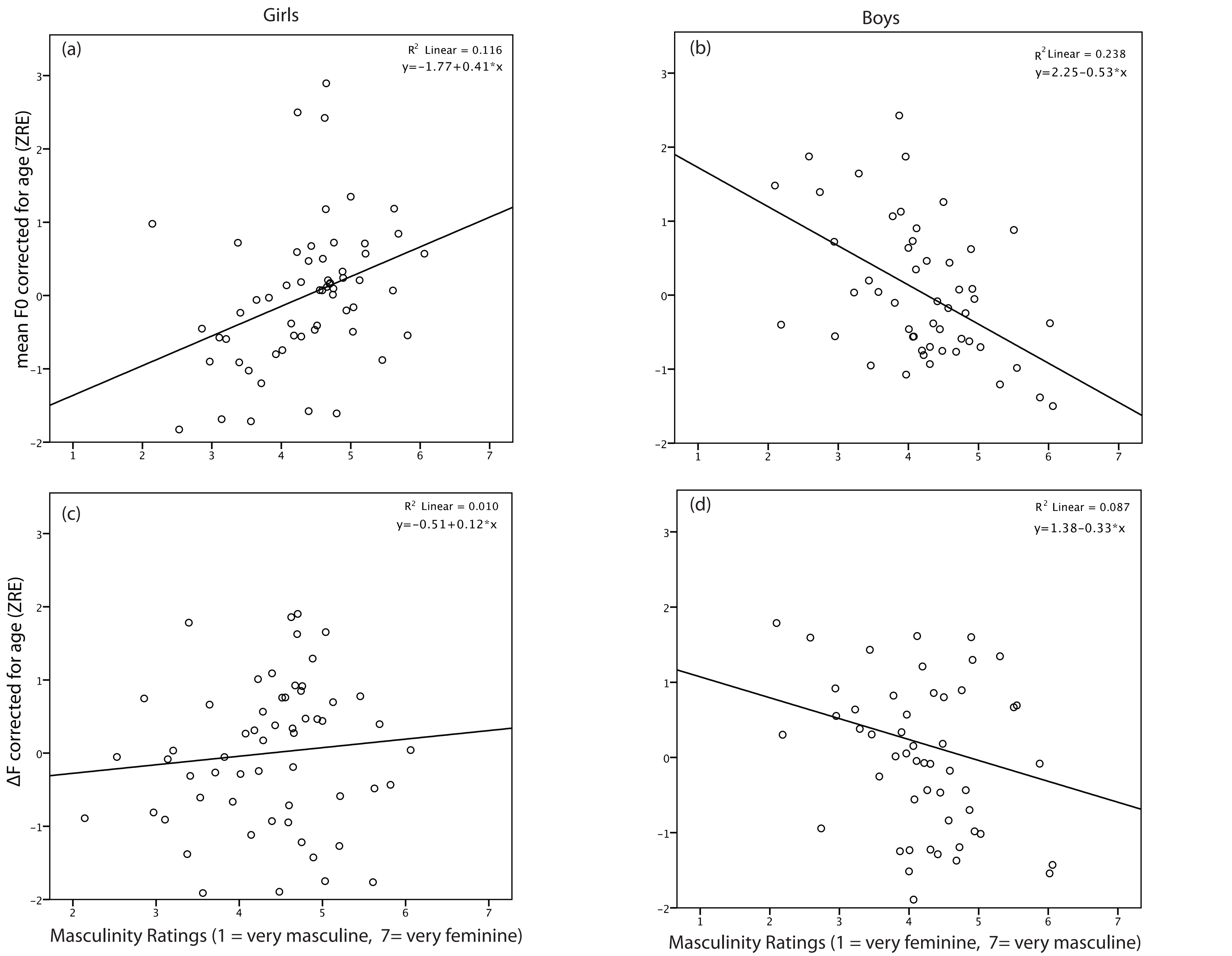
-.02
.06
F0
.33*
.09
.11
PERCEIVED
FEMININITY
.06
ΔF
.09
.11
-.05
HEIGHT



Girls
Boys
(a)
R^2 Linear = 1.710E-4
y=-8E-17-0.01*x
(b)
R^2 Linear = 0.219
y=0.01-0.48*x
(c)
R^2 Linear = 0.029
y=1.13E-15-0.17*x
(d)
R^2 Linear = 0.063
y=4.35E-16-0.25*x
Testosterone corrected for age (ZRE)
mean F0 corrected for age (ZRE)
ΔF corrected for age (ZRE)



Girls
Boys
(a)
R^2 Linear = 0.116
y=-1.77+0.41*x
(b)
R^2 Linear = 0.238
y=2.25-0.53*x
mean F0 corrected for age (ZRE)
(c)
R^2 Linear = 0.010
y=-0.51+0.12*x
(d)
R^2 Linear = 0.087
y=1.38-0.33*x
ΔF corrected for age (ZRE)
Masculinity Ratings (1 = very masculine, 7= very feminine)
Masculinity Ratings (1 = very feminine, 7= very masculine)

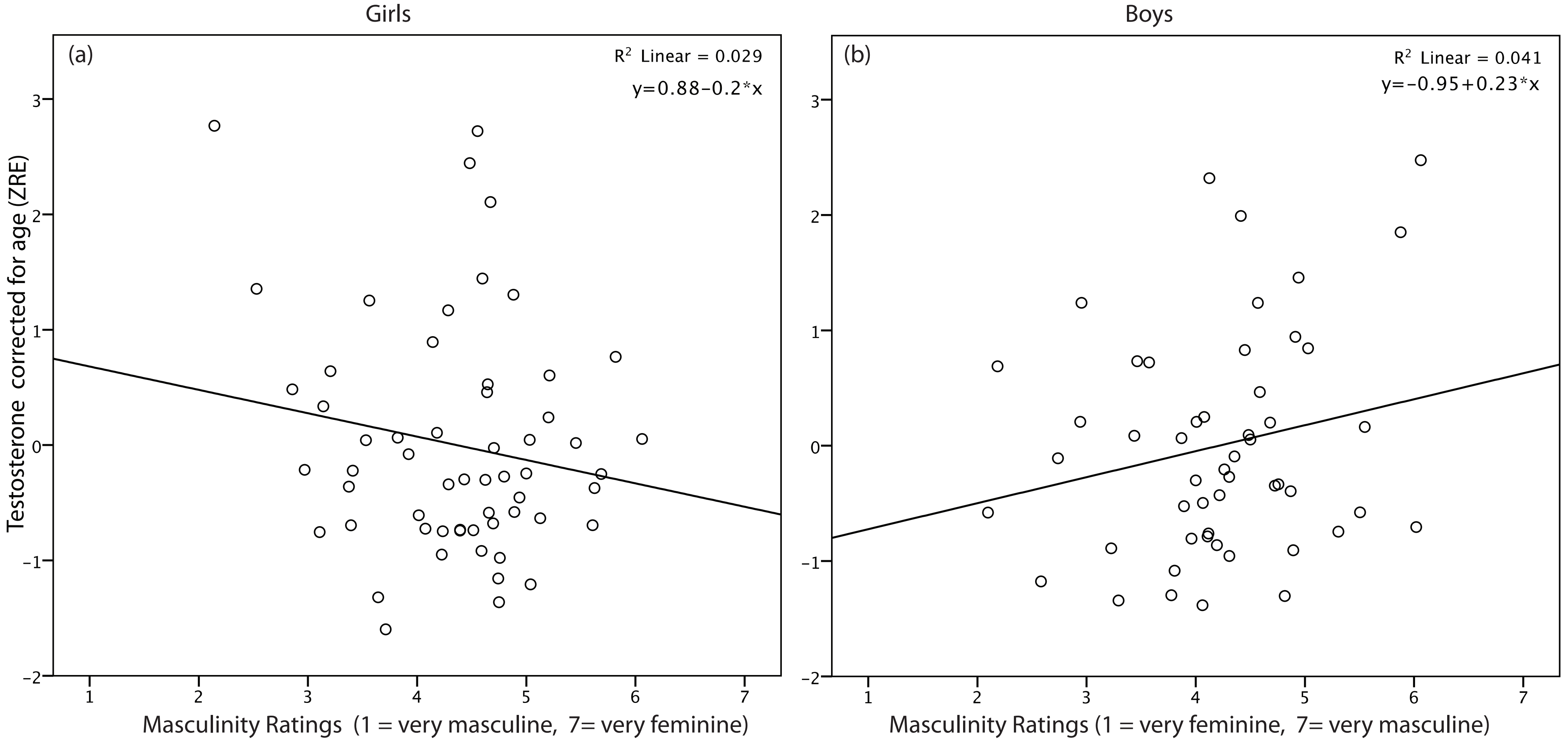

Girls
(a)
R^2 Linear = 0.029
y=0.88-0.2*x
Testosterone corrected for age (ZRE)
Masculinity Ratings (1 = very masculine, 7= very feminine)
Boys
(b)
R^2 Linear = 0.041
y=-0.95+0.23*x
Masculinity Ratings (1 = very feminine, 7= very masculine)

Figure Captions

Figure 1 - Voice characteristics (mean F0 and ΔF in Hz) of pre-prubertal girls (a,c) and boys (b, d). Linear relationships were observed with both parameters decreasing with age.

Figure 2 - Path diagram showing standardised path coefficients for boy speakers. Residuals for F0 and ΔF are allowed to vary. Significant coefficients $p < .05$ are reported with asterisk *.

Figure 3 - Path diagram showing standardised path coefficients for girl speakers. Residuals for F0 and ΔF are allowed to vary. Significant coefficients $p < .05$ are reported with asterisk *.

Figure S1 – Salivary testosterone levels, corrected for age, of pre-prubertal girls (a,c) and boys (b, d) on voice characteristics (mean F0 and ΔF in Hz), also corrected for age. Linear relationships were observed for boys only.

Figure S2 - Voice characteristics (mean F0 and ΔF in Hz) corrected for age, of pre-pubertal girls (a,c) and boys (b, d) on masculinity ratings. Linear relationships were observed in both sexes between mean F0 and masculinity: voices with higher mean F0 were rated as less masculine / more feminine, than those with lower mean F0.

Figure S3 - – Salivary testosterone levels, corrected for age, of pre-prubertal girls (a) and boys (b) on ratings. No significant linear relationships were observed.